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Link Reliable Joint Path and Spectrum Diversity in Cognitive Radio Ad-Hoc Networks

P. Periyasamy
Department of Computer Science and Applications
Sree Saraswathi Thyagaraja College
Pollachi - 642 107, Tamil Nadu, India
Email: pereee@yahoo.com
Dr. E. Karthikeyan
Department of Computer Science
Government Arts College
Udumalpet - 642 126, Tamil Nadu, India
Email: e_karthi@yahoo.com

ABSTRACT

Due to the uncertainty in the available spectral resource, there is a need of inimitable challenges in cognitive radio networks. The most common decisive issue is that the performance degradation in cognitive radio ad-hoc networks (CRAHNs) experienced by cognitive users (CUs) due to the variation in the activity of primary users (PUs) in both frequency and space domain, diversity techniques can be represented an efficient way to address this issue. In this paper, we propose a link reliable joint path and spectrum diversity technique by modifying D2CARP with link quality metric such as CETX instead of hop count for effective use of spectrum in CRAHNs, is referred to as Link Reliable Dual Diversity Cognitive Ad-hoc Routing Protocol (LR-D2CARP). Make use of both link reliable path and spectrum diversities, CUs can switch dynamically to different link reliable paths as well as spectrum bands for communicating with each other in the presence of frequency- and space-varying PU activity. The simulation results reveal the effectiveness of our protocol in CRAHNs.

Keywords: **cognitive radio ad-hoc networks, link reliability, joint path, spectrum diversity, routing, QoS**.

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I. INTRODUCTION

The spectrum efficiency is enhanced in cognitive radio (CR) paradigm by allowing unlicensed users, called cognitive users (CUs), in order to utilize the spectrum dynamically and opportunistically assigned to the primary users (PUs) when it is not temporarily used. This can be attained by changing CUs transmission and reception parameters to communicate with each other without causing interference to the PUs.

Due to the uncertainty in the available spectral resource, there is a need of inimitable challenges in cognitive radio networks(CRNs). The distinguishing factors [1] of cognitive radio ad-hoc networks (CRAHNs) are the distributed multi-hop architecture, the dynamic network topology and the availability of spectrum which varies in time and space. Those factors influence the performance degradation in CRAHNs by CUs because of the activity of PUs which varies both in frequency and space domain. By incorporating diversity techniques together such as path and spectrum diversity in CRAHNs, we can provide an effective solution to address this issue. Most of the recently proposed routing protocols for CRAHNs are not exploiting diversity techniques [2-4]. However, some proposals [5] have resorted to path- or spectrum diversity techniques. A path-diversity routing protocol has been proposed [6] which is operating only on infrastructure-based network. Another path-diversity based routing protocol by assuming a specific distribution of PUs and CUs in CRAHNs have proposed [7] but is not reasonable. A source-based routing protocol with path diversity has been proposed [8] for CRNs but its application in CRAHNs is not reasonable due to high packet header overhead. A cognitive ad-hoc on-demand distance vector (CAODV) routing have been presented for exploiting path and spectrum-diversity individually which leads the PU activity can still degrade the performance of the networks [9,10]. Using global knowledge about the network topology, a near optimal solution to joint routing and spectrum allocation problem in multi-hop CRNs have proposed [11] but it is not reasonable in CRAHNs. In Dual Diversity Cognitive Ad-hoc Routing Protocol (D2CARP) [12], an optimal solution to joint path and spectrum allocation problem has proposed but link stability is not considered. In this paper, we propose a link reliable joint path and spectrum diversity technique by modifying D2CARP with link quality metric such as CETX instead of hop count for effective use of spectrum in CRAHNs, called *Link Reliable Dual Diversity Cognitive Ad-hoc Routing Protocol (LR-D2CARP)*.

The rest of the paper is organized as follows: Section II gives a brief description about the related work. Section III presents the proposed routing protocol. The simulation environment and experimental results are discussed in Section IV. Finally, conclusions and future work are given in Section V.

II. RELATED WORKS

A. Overview of Dual Diversity Cognitive Ad-hoc Routing Protocol (D2CARP)

D2CARP [12] is an extension of a well-studied CAODV [9,10]. The major goals of D2CARP are (i) to show the

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effects of the variation of PU activity on routing in frequency and/or space domain; (ii) to state the benefits of jointly exploiting path- and spectrum-diversity in CRAHNs.

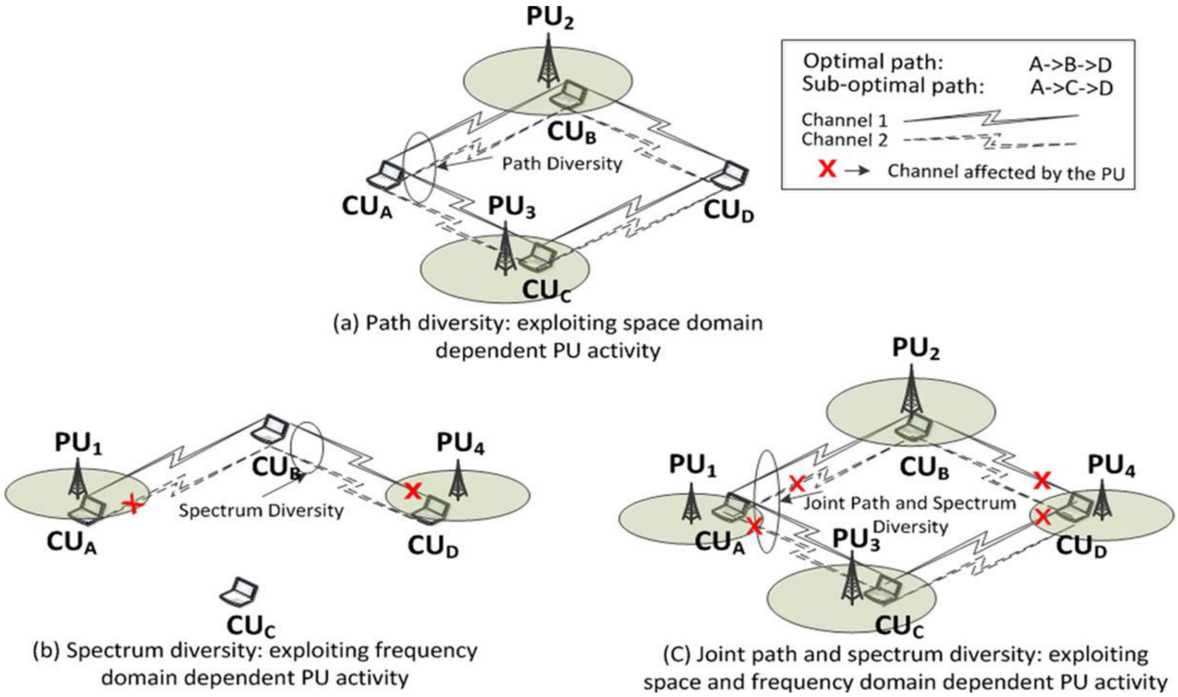

Fig. 1 Illustration of path and/or spectrum diversity [12]

Path diversity

Path diversity is the process of allowing CUs to switch dynamically among different paths for communicating with each other in presence of space-domain-dependent PU activity. From Fig. 1(a), how the variation of PU activity can affect a routing process in space domain. The CU_B and CU_C are under the transmission range of two different PUs. The CU_A can reach CU_D through the optimal path $CU_A \rightarrow CU_B \rightarrow CU_D$ when PU_2 is not active; or the sub-optimal path $CU_A \rightarrow CU_C \rightarrow CU_D$ when PU_2 is active but PU_3 is not active, without the need of a new route discovery process by means of exploiting the path diversity.

However, CU_A cannot reach CU_D when the effect of PU activity varies in frequency domain, as shown in Fig. 1(b) by only exploiting path diversity. CU_A must be able to establish paths through different spectrum bands to communicate with CU_D.

Spectrum diversity

Spectrum diversity is the process of allowing CUs to switch dynamically among different channels for communicating with each other in presence of frequency-domain-dependent PU activity. Fig. 1(b) represents how the variation of PU activity can affect a routing process in frequency domain. The CU_A and CU_D are partially affected by two different PUs on channel 2 and channel 1 respectively. The CU_A can still communicate with CU_D through the optimal path composed by link $CU_A \rightarrow CU_B$ (on channel 1) and $CU_B \rightarrow CU_D$ (on channel 2) without the interference of PUs by means of exploiting the spectrum diversity. However, the performance degradation occurred due to the activity of a PU with which fully affects a path cannot counteract by the only exploitation of spectrum diversity.

Joint path and spectrum diversity

Path diversity cannot counteract the variation of PU activity in frequency domain, whereas spectrum diversity cannot counteract the variation of PU activity in space domain. Joint path and spectrum diversity can provide a promising solution for solving both of the above mentioned limitations. The joint path and spectrum diversity switches CUs dynamically among different paths and channels for communicating with each other in presence of frequency-domain-dependent and space-domain-dependent PU activity.

Fig. 1(c) illustrates how the variation of PU activity can affect a routing process in both space and frequency domain. We assume that CU_A, CU_B, CU_C and CU_D are under the transmission range of four different PUs. The CU_A and CU_D are partially affected by PUs on channel 2 and channel 1 respectively, and CU_B and CU_C are fully affected by PU_2 and PU_3 respectively.

The greatest benefit of jointly exploiting path and spectrum diversity, CU_A can communicate with CU_D through the optimal path established by link $CU_A \rightarrow CU_B$ (on channel 1) and $CU_B \rightarrow CU_D$ (on channel 2) when PU_2 is not active; or the sub-optimal path established by link $CU_A \rightarrow CU_C$ (on channel 1) and $CU_C \rightarrow CU_D$ (on channel 2) when PU_2 is active but PU_3 is inactive. The CU_A can now reach CU_D counteracting the effect of PU activity by means of jointly exploiting path and spectrum diversity.

Dual diversity cognitive ad-hoc routing protocol (D2CARP) is a routing protocol designed for CRAHNs by taking the local observations of PU activity into account.

The main feature of D2CARP is to jointly exploit the path and spectrum diversity in routing such that the CUs can switch dynamically among different paths and channels by means of local route decisions during the data transmission. Even though D2CARP shares some common functionality with CAODV, it is distinguished from CAODV that is the route discovery process of D2CARP starts with broadcasting of a Route REQuest (RREQ) packet by the source to neighbors on each channel not affected by a PU activity and ends with one or several routes set up after the reception of Route REPlies (RREPs) from the destination. The source can take advantage of joint path and spectrum diversity by means of multi-path and multi-channel routes at the end of the route discovery process. When PUs activity occurs while the channel is occupied by a CU, it vacates the channel and looks for another available channel for continuing the communication with its neighbor. Whenever there is no free channel for its neighbor, the CU recalls the route discovery process. The D2CARP does not ensure link reliable paths because it selects routes based on only hop count.

B. Routing Metrics

The qualitative measures to select best routes among multiple routes under certain aspects of the routing process of a protocol are called ***Routing Metrics*** [13]. These metrics are classified as ***(i) node based routing metrics*** which select the best routes among multiple routes based on available information of participating nodes such as energy, hop count, etc., and ***(ii) link based routing metrics*** which select the best routes among multiple routes based on available information of participating links such as throughput, bandwidth reliability, etc. Reliable communication has been an issue in CRAHN since the nodes prone to failures due to uncertainty links between them.

The conventional node based routing metric is called ***Hop count*** or ***Path length*** [14] which select a route with less number of hops among the available routes to the intended destination from the source. Many of the routing protocols in CRAHN use hop count as their base metric. Although, it is very simple and easy to evaluate the suitability of a route but it does not take packet loss or link's bandwidth or quality or node's energy into account.

Expected Transmission Count (ETX) [15] estimates the number of transmissions and retransmissions needed to send a data packet over a link, called link ETX. The ETX value of a link between any two participating nodes of the route, called $ETX_{link(i,j)}$, is calculated from both uplink quality from the sender to the receiver $PRR_{forward(i,j)}$ and downlink quality from the receiver to the sender, $PRR_{backward(i,j)}$.

$$ETX_{link(i,j)} = \frac{1}{PRR_{forword(i,j)} \times PRR_{backward(i,j)}} \quad (1)$$

The values for $PRR_{forward(i,j)}$ and $PRR_{backward(i,j)}$ are determined in terms of number of RREQ/RREP packets transmitted over a period of time as follows:

$$PRR_{forward(i,j)} = \frac{\text{No. of RREQ / RREP packets generated at node } i}{w \sec onds} \quad (2)$$

$PRR_{forward(i,j)}$ is the **P**acket **R**eception **R**ate of uplink quality from the sender to the receiver, that is, the number of RREQ or RREP packets generated from the sender to the receiver over a period of time.

$$PRR_{backward(i,j)} = \frac{\text{No. of RREQ / RREP packets received at node } j}{w \sec onds} \quad (3)$$

$PRR_{backward(i,j)}$ is the **P**acket **R**eception **R**ate of downlink quality from the receiver to the sender, that is, the number of RREQ or RREP packets received by the receiver from the sender over a period of time.

Cumulative Expected Transmission Count (CETX or e2e-ETX) [16] is the summation of the ETX of all participating links of the route, called ***path ETX*** or ***Path-Link Quality Estimator (P-LQE)***. Received Signal Strength Indicator (RSSI) is determined initially by RREQ or RREP during route discovery and then by HELLO packets during route selection and maintenance. Since the RREQ or RREP packets are used to determine the stability of links between nodes during route discovery, they are used to calculate both ETX and CETX in this protocol. In this paper, the ETX of a link between nodes along the forward path is computed using RREP packets as well as the ETX of a link between nodes along the reverse path is computed using RREQ packets. The CETX value of the route is computed as follows:

$$CETX_{path(S,D)} = \sum_{link(i,j) \in path(S,D)} ETX_{link(i,j)} \quad (4)$$

Where *path(S, D)* is a set of successive links in the path from node S to D such as: $path(S, D) = \{(S, I_1), (I_1, I_2), \ldots, (I_{k-1}, I_k), (I_k, D)\}$.

III. PROPOSED PROTOCOL

Our multipath routing protocol is a slight modification of D2CARP which generates link reliable paths for jointly exploiting path and spectrum diversity in frequency and space domain in CRAHNs. Our protocol reduces energy consumption, routing overhead, normalized routing overhead with varying number of PUs and CUs. It also improves packet delivery ratio and throughput with varying number of PUs and CUs.

A. Route REQuest phase

Let us consider an arbitrary node, say X, receiving a RREQ packet from node Y through a channel which is free from PU activity, say channel c in RREQ phase. Fig. 2 describes how LR-D2CARP exploits joint path and spectrum diversity in RREQ phase.

When node X receives the first RREQ, then it calculates CETX and creates a reverse path toward the sender node Y through the channel c and it broadcasts a copy of the RREQ packet through each idle channel.

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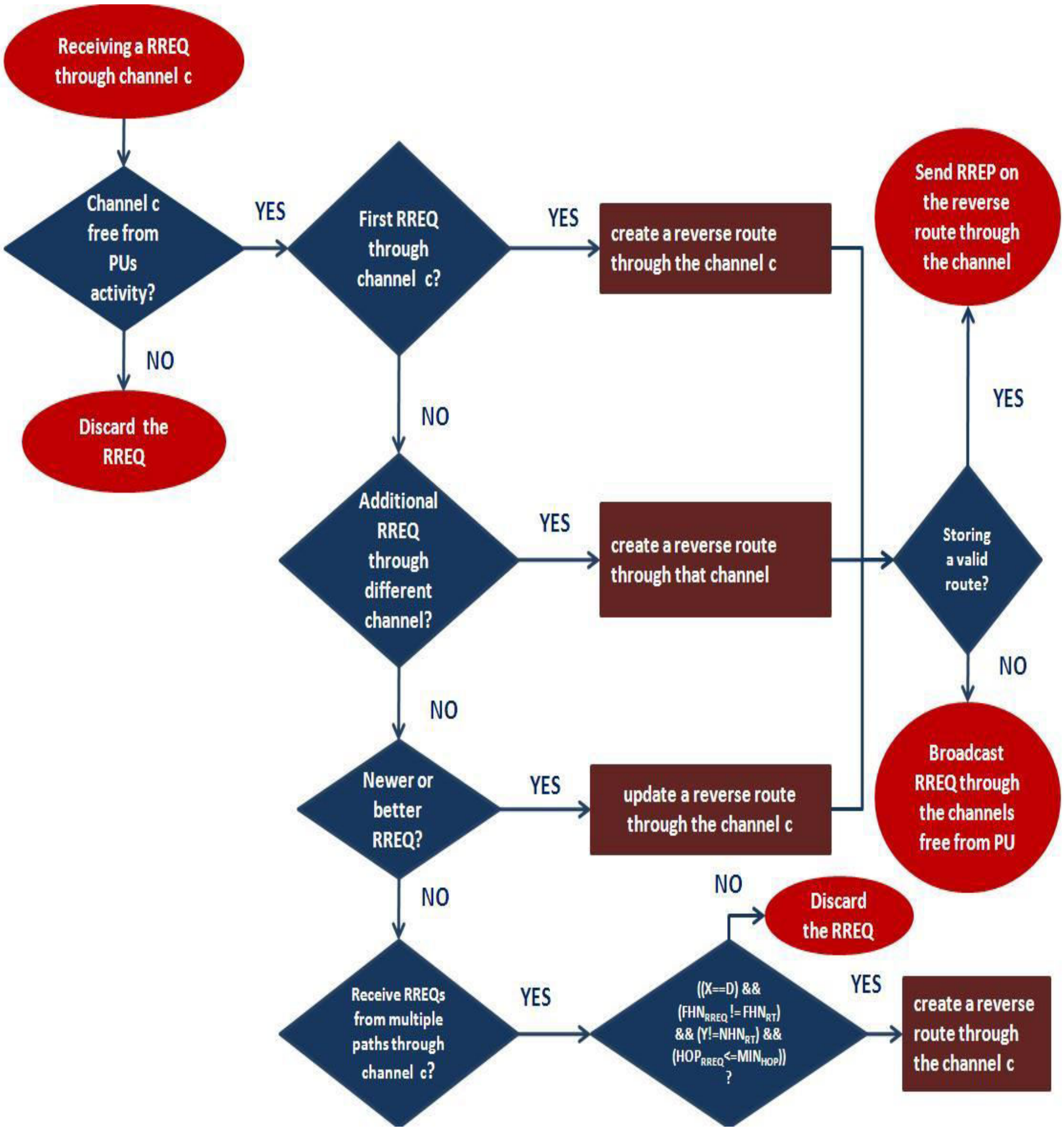

Fig.2 Route request flow chart for LR-D2CARP

If node X receives a further RREQ from the same neighbor Y, but on a different channel and $CETX_{RREQ}$<=$CETX_{RT}$, then it creates a reverse route only through that channel. In such a way, node X is able to create reverse routes through the multiple idle channels. Moreover, if node X receives a new or better RREQ and $CETX_{RREQ}$<=$CETX_{RT}$, then it updates the reverse route through the channel c. When a node receives a RREQ directly from a source then the receiving node's ID is kept in the first hop node (FHN). If X is the destination node and FHN of RREQ (say FHN_{RREQ}) is not equal to stored FHN (say FHN_{RT}) and hop count of RREQ is less than or equal to the minimal hop count of the routes between the source and destination then the node creates a reverse route through channel c, otherwise it drops the packet.

B. Route REPly phase

Let us consider an arbitrary node; say P, receiving a RREP packet from node Q through an idle channel, say channel c in RREP phase. Fig.2 describes how LR-D2CARP exploits joint path and spectrum diversity in RREP phase.

When node P receives the first RREP packet, then it calculates CETX and creates a forward route through channel c and forwards RREP to all channels that have reverse route. If node P receives a further RREP from the same neighbor Q, but on a different channel and $CETX_{RREP}$<=$CETX_{RT}$, then it creates a forward route and forwards RREP only through that channel. Node P is able to create forward routes through the multiple idle channels in such a way. When a node receives a RREP directly from a destination then the receiving node's ID is kept in the first hop node (FHN). If P is the destination node and FHN of RREP (say FHN_{RREP}) is not equal to stored FHN (say FHN_{RT}) and hop count of RREP is less than or equal to the minimal hop count of the routes between the source and destination then the node creates a forward route through channel c, otherwise it drops the packet.

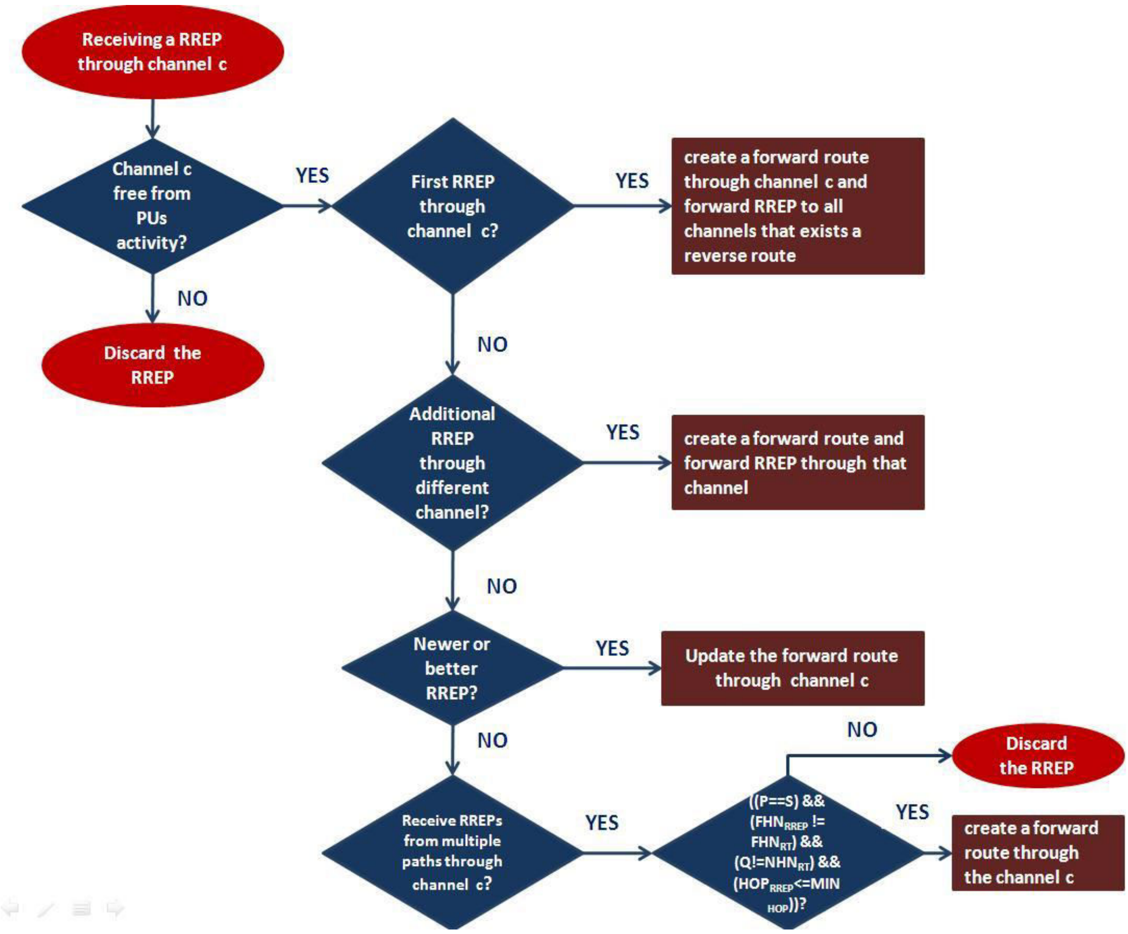

Fig.3 Route reply flow chart for LR-D2CARP

IV. SIMULATION ENVIRONMENT AND EXPERIMENTAL RESULTS

A. Simulation Parameters

Table 1 Simulation Parameters

Parameter	Value
Simulator	NS-2.34
MAC Type	802.11
Simulation Time	1060 seconds
Channel Type	Wireless Channel
Routing Protocols	D2CARP & LR-D2CARP
CU transmission range	120 m
Data Traffic model	Constant bit rate (CBR) over UDP
Data Payload	512 bytes/packet
CU number	[20, 40 . . . , 160]
PU number	[10, 12 . . . , 18]
Radio Propagation Model	Two Ray Ground
PU Tx range for the overlapped channel i	300 m
PU Tx range for adjacent channels (i − 1, i + 1)	150 m
PU Tx range for adjacent channels (i − 2, i + 2)	75 m
PU activity parameter	200
Active data traffic interval	[60–1000]
Interface Queue Length	50
Interface Queue Type	DropTail/PriQueue
CU speed	2 m/s
CU node density	400 nodes/Km^2
Mobility Model	Random Waypoint (RWM)
Idle Power	0.0001
Transmission & Receiving Power	1.0
Sleep Power	0.0001
Transition Power	0.002
Transition Time	0.005
Initial Energy	100 Joules

We evaluate and compare the performance of **D2CARP** and **LR-D2CARP** under the simulation parameters illustrated in Table 1 using NS 2.34 [17,18,19].

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B. Experimental results and Discussion

We evaluate the performance of LR-D2CARP and compare it with D2CARP using the six different performance metrics given below:

(i) *Average End-to-End delay* is the average time of the data packet to be successfully transmitted across a CRAHN from source to destination. It includes all possible delays such as buffering during the route discovery latency, queuing at the interface queue, retransmission delay at the MAC, the propagation and the transfer time.

(ii) *Routing overhead* is the total number of control packets or routing packets generated by routing protocol during simulation.

(iii) *Normalized Routing overhead* is the number of routing packets transmitted per data packet towards destination during simulation.

(iv) *Total Energy consumed* is the summation of the energy consumed by all nodes in the simulation environment. i.e., *energy consumed by a node = initial energy of that node – residual energy of that node*.

(v) *Throughput* is the number of bytes received successfully.

(vi) *Packet Delivery Ratio* is the ratio of data packets delivered to the destination to those generated by the sources.

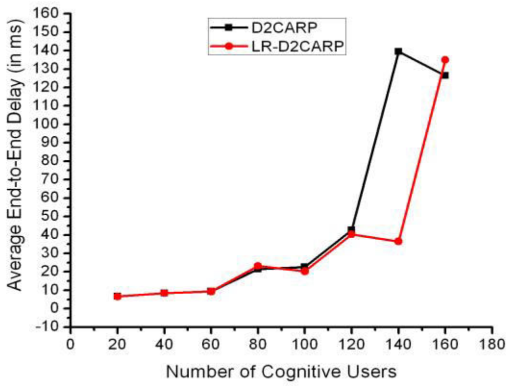

Fig. 4 Average End-to-End Delay (in ms) of D2CARP & LR-D2CARP

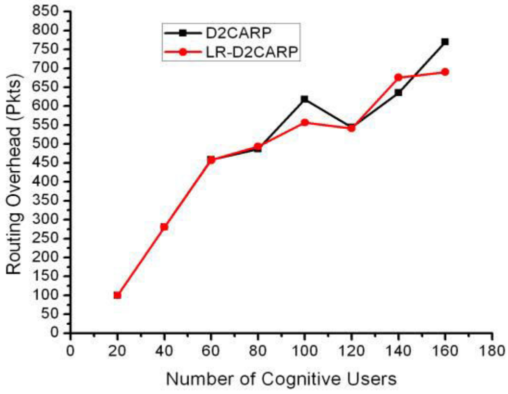

Fig. 5 Routing Overhead (in pkts) of D2CARP & LR-D2CARP

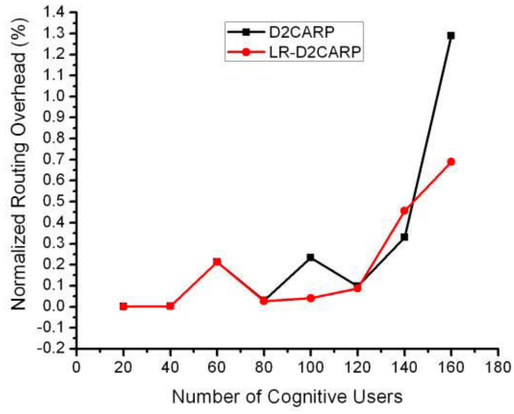

Fig. 6 Normalized Routing Overhead (in %) of D2CARP & LR-D2CARP

When the numbers of CUs varying in incremental basis the average end-to-end delay, routing overhead, normalized routing overhead and total energy consumed are significantly reduced by LR-D2CARP than D2CARP because LR-D2CARP exploits the joint path and spectrum diversity based on link metric CETX which ensures link reliability during data transmission shown in Fig. 4 – Fig.7 respectively.

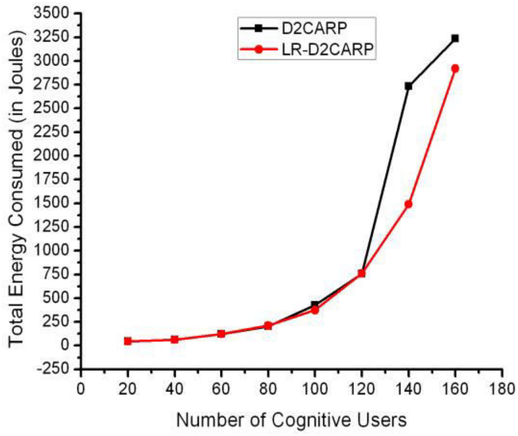

Fig. 7 Total Energy Consumed (in Joules) of D2CARP & LR-D2CARP

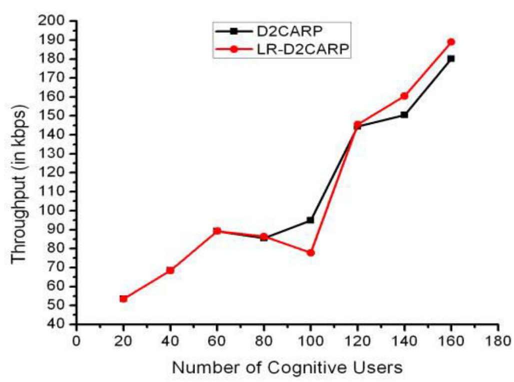

Fig. 8 Throughput (in kbps) of D2CARP & LR-D2CARP

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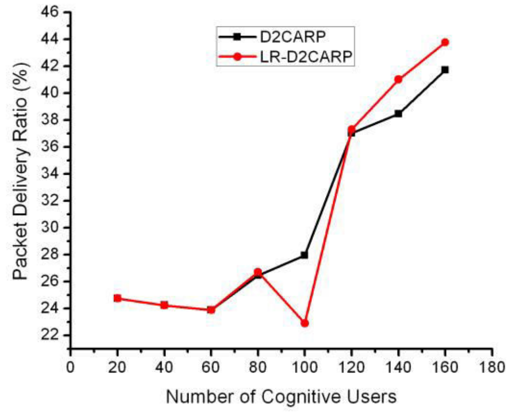

Fig. 9 Packet Delivery Ratio (%) of D2CARP & LR-D2CARP

When the numbers of CUs varying in incremental basis the throughput and packet delivery ratio are significantly increased by LR-D2CARP than D2CARP because LR-D2CARP exploits the joint path and spectrum diversity based on link metric CETX which ensures link reliability during data transmission shown in Fig. 8 and Fig. 9 respectively.

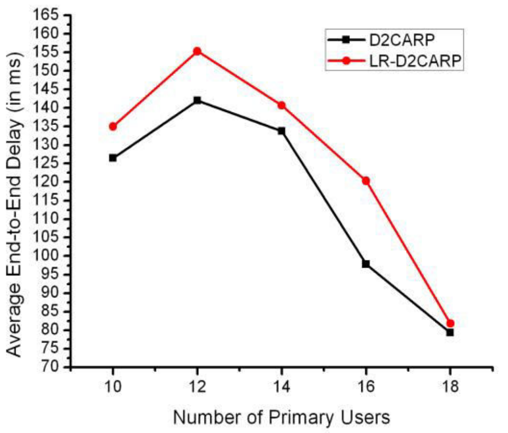

Fig. 10 Average End-to-End Delay (in ms) of D2CARP & LR-D2CARP

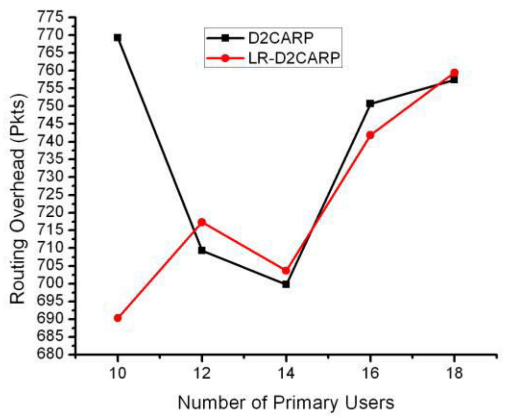

Fig. 11 Routing Overhead (in pkts) of D2CARP & LR-D2CARP

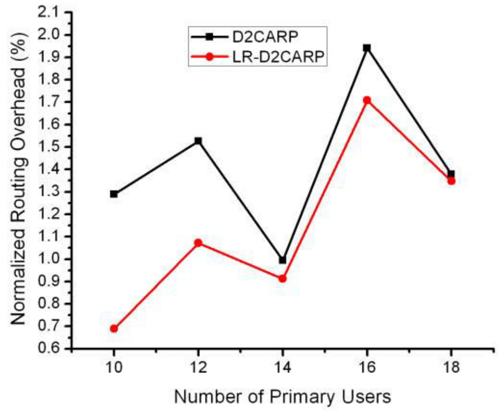

Fig. 12 Normalized Routing Overhead (in %) of D2CARP & LR-D2CARP

When the numbers of PUs varying in incremental basis the routing overhead, normalized routing overhead and total energy consumed are significantly reduced by LR-D2CARP than D2CARP because LR-D2CARP exploits the joint path and spectrum diversity based on link metric CETX which ensures link reliability during data transmission shown in Fig. 11 – Fig.13 respectively.

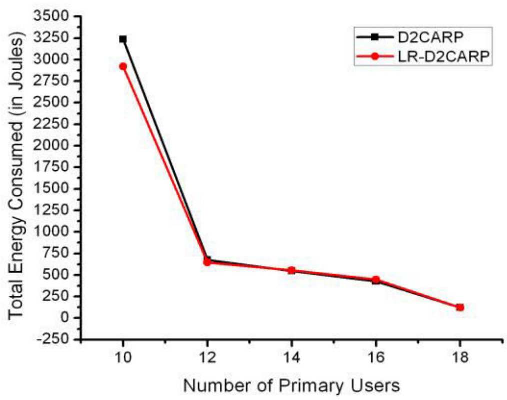

Fig. 13 Total Energy Consumed (in Joules) of D2CARP & LR-D2CARP

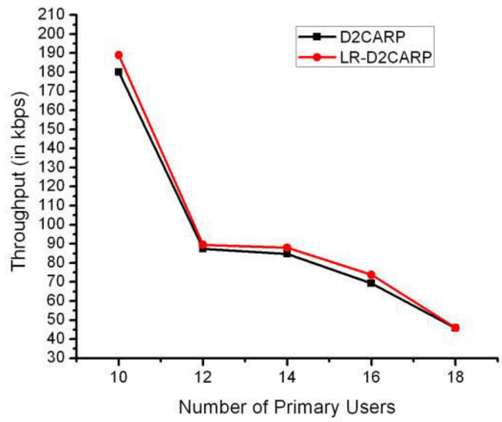

Fig. 14 Throughput (in kbps) of D2CARP & LR-D2CARP

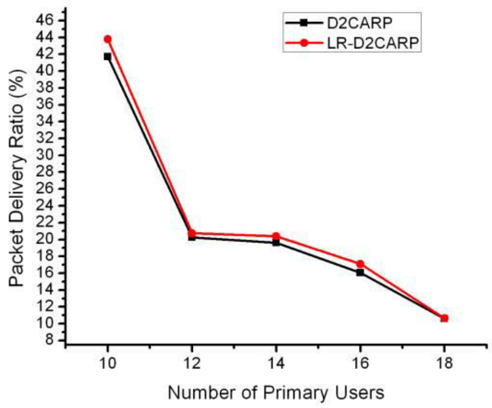

Fig. 15 Packet Delivery Ratio (%) of D2CARP & LR-D2CARP

When the numbers of PUs varying in incremental basis the throughput and packet delivery ratio are significantly increased by LR-D2CARP than D2CARP because LR-D2CARP exploits the joint path and spectrum diversity based on link metric CETX which ensures link reliability during data transmission shown in Fig. 14 and Fig. 15 respectively.

V. CONCLUSION AND FUTURE WORK

We proposed LR-D2CARP by slightly modifying the D2CARP which generates link reliable paths for jointly exploiting path and spectrum diversity in frequency and space domain in CRAHNs. This protocol reduces energy consumption, routing overhead, normalized routing overhead with varying number of PUs and CUs. It also improves packet delivery ratio and throughput with varying number of PUs and CUs. Simulation results show that the effectiveness of LR-D2CARP.

In future we will reduce the average end to end delay when the PUs varies is shown in Fig. 10 and the overall performance considering new metrics associated with network nodes such as networks lifetime and reduction in average number of nodes dying in different mobility models by studying and enhancing recent power efficient strategies.

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